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INFLUENCE OF WATER INJECTION RATE ON THE VORTECONE, AN IMPINGEMENT SCREEN, AND A CONVENTIONAL FILTER SCREEN CLEANING EFFICIENCY

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INFLUENCE OF WATER INJECTION RATE ON THE VORTECONE, AN IMPINGEMENT SCREEN, AND A CONVENTIONAL FILTER SCREEN CLEANING EFFICIENCY

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering in the College of Engineering at the University of Kentucky

By
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Lexington, Kentucky 2019

ABSTRACT OF THESIS

INFLUENCE OF WATER INJECTION RATE ON THE VORTECONE, AN IMPINGEMENT SCREEN, AND A CONVENTIONAL FILTER SCREENCLEANING EFFICIENCY

Industrial produced respirable particles are known to affect the respirable tract of workers causing serious illness or even death. These particles can be found in any mining operation's environment, new regulations by the Mine Safety and Health Administration (MSHA) in 2014 reduced the allowable limit of dust exposure for underground workers. Dust control practices have been improving over the years to lower the number of incidents caused by these particles. In underground mining, water sprays and scrubber systems have become the most used dust control methods. Water sprays create numerous fine water droplets to capture dust once it has become airborne.

The goal of thesis is to determine the influence of water injection on cleaning efficiency of the Vortecone scrubber, a device used to remove paint overspray particles from the airstream in the automotive industry. The Vortecone is compared to a non-clogging screen developed at the Department of Mining Engineering, University of Kentucky, and the conventional screen found in a flooded-bed dust scrubber system in a continuous miner. Tests were done in a random order to prevent experimental contamination; all experiments were repeated three times in order to minimize any systematic errors in the procedures. A total of 18 tests were run to determine the relation between the amount of water flow injected into the system and the cleaning efficiency on each one of the filter systems. Water flows were set at 2.0 gpm (7.57 lit/min), 4.0 gpm (15.12 lit/min) and 6.0 gpm (22.72 lit/min). Additionally, tests were also run in a dry condition (no water flowing through the system), so that the difference between the cleaning efficiency curves with and without water flow could be compared. Airflows were set at 600 cfm and 800 cfm (0.28 m^3/s and 0.38 m^3/s respectively). JMP statistical software was used to generate the sequence in which the tests were conducted. The results of this study show that both the Vortecone and the impingement screen have great cleaning efficiency overall compared to the conventional screen.

The conventional fibrous screen is the only water flow-rate dependent system, while the Vortecone is the filter that requires the lowest amount of water to achieve the best dust capturing rate.

KEYWORDS: Vortecone, Cleaning efficiency, Dust Scrubber, Impingement screen

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08/14/2019

Date

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DEDICATION

Para mi familia. Sin ellos no estuviese donde estoy.

ACKNOWLEDGMENTS

First, I thank God, our Father, friend, who has helped me to complete this thesis and my master's degree. I would like to thank my Parents, who with their effort and love supported me unconditionally during the process of formation, inspiring me day after day to continue. To Dr. Steven Schafrik and Dr. Ashish Kumar for being my mentors, your guidance was invaluable for the completion of my degree, I will always be grateful. I would also like to thank Dr. Thomas Novak and Dr. Zacharias Agioutantis for being my graduate committee members. Finally. I would like to acknowledge all my friends who contributed their grain of sand to the elaboration of this thesis, and all who accompanied me during this amazing journey.

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Chapter 1 Introduction

1.1 Background and Motivation

Since the early 1990s, the incidence of coal workers' pneumoconiosis (CWP) and other chronic diseases related to dust particle inhalation in underground mines have been increasing, according to a study conducted by the National Institute for Occupational Safety and Health (NIOSH, 2008). There have been sustained efforts to improve the environment of underground mines to reduce dust exposure of the workers and to minimize the onset of these exposure related diseases. The Mine Safety and Health Administration (MSHA) has decreed new regulatory measures to accomplish to help accomplish the previously mentioned efforts (MSHA, 2014).

Research has shown that coal dust is the main factor that causes CWP due to the fact that a portion of the generated dust has an aerodynamic diameter less than 10 µm, placing it in the respirable range. This dust is a consequence of any breaking or crushing of coal rock, making it a significant health issue to miners (WHO, 1999).

Many underground mine accidents involving dust-related explosions have happened in recent years, one of them being the one at the Upper Big Branch mine, West Virginia, in 2010. This catastrophic event was attributed to a methane deflagration event acting as the precursor to a deadlier coal dust explosion. This, and numerous other explosion events leading to fatalities, has led mine operators to investigate remedial measures to combat dust.

Over the years, several dust control methods have been tested in mines to control the levels of coal dust particles. Several of them have proven to be very effective; therefore, they have been used frequently. Some of the methods include dilution of generated dust to safe levels, displacement by ventilation, wetting and capture by water sprays, and collection and filtration by dust collector (Kissell, 2003).

Continuous miners are used in the vast majority of coal mines around the world. These machines are operated against blind headings; therefore, ensuring adequate flow of air at the face can be difficult. The minimum requirement of ventilation airflow quantities at those coal faces are legislated to dilute dust to harmless levels. Water sprays are also installed at strategic locations and serve as powerful air-movers. The sprays capture some amount of dust generated while cutting. These water sprays are also powerful air-movers, which lower the exposure of miners stationed nearby. In addition to this, continuous miners are usually equipped with a flooded-bed dust scrubber, as shown in Figure 1, in order to capture the dust from the extraction drum (Chao, 2000); (Wala, 2008); (Organiscak, 2010).

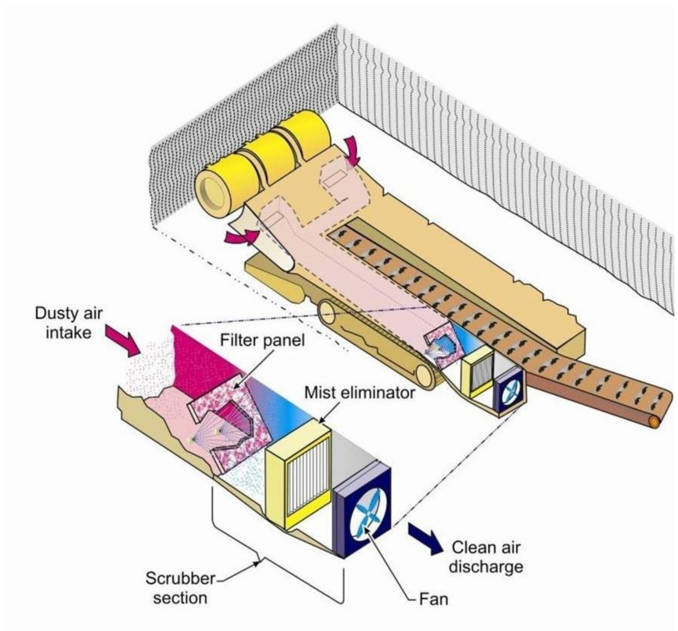

Figure 1.1: A schematic of a flooded-bed dust scrubber (Source: CDC)

These scrubbers are usually powered by a vane-axial flow fan, and they arrest dust particles on a multi-layered fibrous type impingement screen. The screen is kept flooded with water, which increases the probability of the particles being captured. A demister installed downstream removes the spent dirty water from the airstream and forces it into a sump at the bottom of the scrubber system. Clean air is discharged at the back of the continuous miner and away from the coal face (Gillies, 1982); (Colinet, Reed, & Potts, 2014). An efficient dust scrubbing system also assists extended cuts (Wala, 1998).

The flooded-bed dust scrubbers have been proven effective in capturing dust particles. However, the conventional fibrous screen is prone to clogging, depending on the coal seam being worked. Clogging increases the resistance of the scrubber system, and the quantity of air being sucked in greatly impairs efficiency (Kissell, 2003). Therefore, even though the cleaning efficiency of the scrubber has improved, the capture efficiency has been reduced, decreasing the overall operational efficiency of the scrubbing system.

1.2 Research Goals

The goal of this project is to determine the impact of water influx in cleaning efficiency of dust scrubbing systems such as the Vortecone, invented at the University of Kentucky and employed by Toyota Manufacturing. The Vortecone is a conventional screen used in flooded-bed dust scrubber systems, with an impingement non-clogging screen designed by the Mining Engineering Department at the University of Kentucky. Laboratory experiments were established to determine the relation between the amount of water flow injected into the system and the cleaning efficiency on each one of the previously mentioned filter systems.

1.3 Organization of the Thesis

This thesis has the following structure. Chapter 2 summarizes some of the important research in the areas of dust-control, such as regulations, dust sampling and technology, and practices to fight against dust in underground coal mines. The fundamentals of aerosols, theory of filters and impactors are discussed in Chapter 3. A detailed description of the laboratory set-up and all the equipment used is discussed in Chapter 4. Chapter 5 summarizes all the conducted experiments and discussions regarding the obtained results. All the major findings, conclusions of this project, and avenues of future work are detailed in Chapter 6.

Chapter 2

2.1 Dust as a Health Hazard

A considerably large amount of particles is generated in most unit operations in a mining environment. Dust is one of the particles that have been closely studied in order to reduce the health and safety hazard risks to which the miners are daily exposed. A long period of exposure to coal dust is known to cause coal worker pneumoconiosis (CWP) in miners.

This disease, also known as black lung, has existed since the very beginning of coal mining (Arnold, 2016). In the 1830s, British doctors started recording lung problems that coal miners were suffering, these examinations are considered to be some of the earliest recorded (McIvor & Johnston, 2007). Knowledge of the aforementioned disease continued to improve into the early 1900s. At this time, however, there was little improvement in the way of legislation controlling levels of respirable coal dust (Arnold, 2016).

A strike by the United Mine Workers of America (UMWA) in 1968 resulted in the creation of the Federal Coal Mine Health and Safety Act (Coal Act) in 1969 (Arnold, 2016). Research at the National Institute for Occupational Safety and Health (NIOSH) has concluded that thousands of coal miners have died from diseases related to mine-dust exposure (NIOSH, 2011).

A higher incidence of black lung in young miners is an additional cause for concern because coal worker pneumoconiosis has no known treatment. An epidemiological data analysis on CWP in the United States from 1960 to 1988 was conducted by Attfield and Castellan at NIOSH. They found that the incidence rate of this disease had been in steady decline during those years, attributed to Coal Act safety legislation (Attfield & Castellan, 1992). However, the occurrence of CWP has seen an increase starting in the early 1990s, and in recent years a significant amount of cases have been reported in the eastern United States, more specifically in the Appalachian region (Blackley, 2016).

The United States is not the only place where studies related to the detrimental aspects of dust particles inhalation have been carried out. In Western Australia, Armstrong surveyed hundreds of miners, looking for respiratory symptoms (Armstrong, 1979). In this study, gold miners tended to show more diseases related to the respiratory tract. Hurley et al. analyzed the radiological data with a 20 years span of about 2,600 coal miners at ten British collieries (Copland, 1982). The presence of CWP in a miner's body was higher when it was exposed to higher amounts of coal dust according to Hurley's study. All these findings showed that exposure-related diseases are common in mining-environments, and hence, more research needs to be done in order to reduce miners' chances of contracting these illnesses.

2.2 Dust as a Safety Hazard

Multiple disasters have occurred in underground coal mines due to deficient dilution of float dust resulting in explosions. This has caused many fatalities. Coal dust explosions are in most of cases deadly and are triggered by less deflagrations or methane ignitions. A total of 367 coal miners working at Monongah Mine, West Virginia, were killed in an explosion on December 6th 1907. After a roof fall accident that caused an explosion at the Jim Walter No. 5 Mine in Brookwood, Alabama, 13 miners lost their lives on September 24th 2001 (Redmayne, 1914). The Senghenydd Colliery explosion, as shown in Figure 2.1, in Britain on October 14th 1913 killed 439 miners (McKinney, et al., 2002).

Another accident took place in West Virginia at the Sago Mine on January 2nd 2006, wherein only one miner out of 13 survived the explosion that trapped the group (Gates, et al., 2007). One of the most recent and well-known accidents in the United States happened at the Upper Big Branch in West Virginia on April 5th 2010, where a massive explosion took the lives of 29 miners. Research by the Mine Safety and Health Administration (MSHA) concluded that the accident was caused by a coal-dust explosion triggered by a methane explosion at the longwall face (Page, et al., 2010).

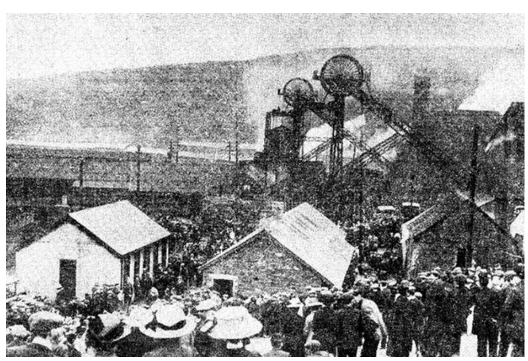

Figure 2.1: The Universal Colliery, Senghenydd in 1913 (Source: Daily Post UK. 14 October 2013)

Many investigations have been carried out to detail mine accidents in United States and China (Gao, 2016) (Cheng, 2015) . According to the results of these studies, there have been numerous efforts put in place by mining companies. Even though there has been a decrease in amount of accidents, all safety measures must be followed by mine operators to avoid chances of recurrence.

2.3 Mine-Safety Legislation in the United States

In 1910, Congress created the US Bureau of Mines to conduct investigations focused on improving safety to reduce accidents in mines. In 1941, federal inspectors were given the right to enter mines. The agency was imparted a limited enforcement authority via the Federal Coal Mine Health and Safety Act of 1952. In November 20th 1968, an explosion in the Farmington Coal Mine that killed 78 miners, guided the way for the reform of the Federal Coal Mine Health and Safety Act of 1969 (MSHA, 1969). This Act stated that at least two annual inspections had to be done on every surface of operation, and at least four in underground coal mines in the United States.

The Federal Mine Safety Act of 1977 (MSHA, 1977) was approved leading to the establishment of MSHA as an independent organization to monitor the health and safety in mines across the country. The Mine Improvement and New Emergency Response (MINER) Act (MSHA, 2006) was approved in 2006 and required all miners to plan specific actions to deal with emergency situations. The Final Rule (MSHA, 2014) established a limit on dust concentration and level of exposure of miners, and it was passed into law in 2014. Most of these laws and acts were approved immediately as consequence of coal dust explosions and other mine related disasters.

2.4 Dust-Standards, Sampling and Technology

Because small particles represent small masses, particulate matter tends to be difficult to measure and special equipment must be used to accomplish this (Amaral, 2015). There is a wide variety of measuring methods in the market, so users can choose depending on the type of measuring and the cost of the device (Amaral, 2015). Particles with smaller size are more difficult to measure and require an expensive instrument to read the particles accurately (Amaral, 2015). Particle measurement instruments can be classified in three ways: gravimetric, optical, and microbalance methods (Amaral, 2015).

Gravimetric methods of measuring aerosol particles are used in collecting a representative sample from an airstream, depositing it on a filter or plate and comparing the weight of the filter to obtain an average mass concentration (Amaral, 2015). A gravimetric sampler is shown in Figure 2.2. This method is mainly used for personal sampling in a certain environmental situation, following the standards that are written in terms of the amount of a mass per unit volume of air to which a worker may be exposed (Amaral, 2015).

Nonetheless, if sample particles are too small, a very sensitive weighing instrument must be used in a controlled environment in order to get the most accurate results when applying the gravimetric sampling technique (USEPA, 2016). For instance, when measuring a particle below 2.5 microns in size, the United States Environmental Protection Agency requires certain conditions that require the assembly of a room with specialized air handling equipment, which includes a controlled temperature to within two degrees °C (35.6 °F) and a relative humidity between thirty and forty percent. In addition, it must be relatively vibration-free to avoid any type of errors in the reading process (USEPA, 2016).

Figure 2.2: Gravimetric sampling pump system (Source: Dust Sampling Instrumentation and Methods, NIOSH, CDC)

Personal dust monitors (PDM), as shown in Figure 2.3, are being used by miners to sample and report concentrations of dust in real time. This allows miners to take corrective actions to reduce their levels of exposure.

Figure 2.3: Personal dust monitor for real-time sampling (Source: CDC)

In 2006, Gillies and Wu examined a new real-time PDM developed by Thermo Electro Corporation. They determined that it could analyze multiple dust sources in a mine (Gillies & Wu, 2006). Figure 2.4 shows how the sampler takes in the dirt-laden air to the sample filter. The oscillation frequency of the micro-balance with the filter is calibrated to the accumulated dust-sample, which reduces with build-up.

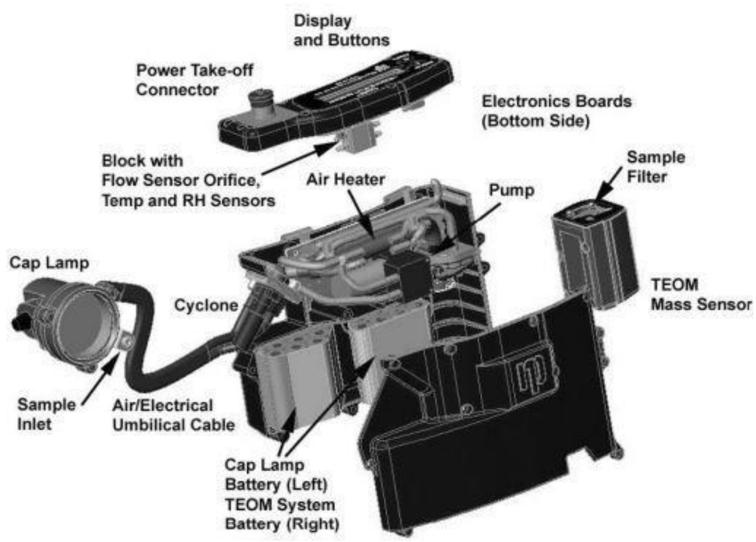

Figure 2.4: An exploded view of the personal dust monitor (Gillies & Wu, 2006)

The MSHA 'Final Rule'

The Mine Safety and Health Administration (MSHA) in the United States is in charge of enforcing the standards and ensuring that safety regulations are being properly followed in mine operations. This organization has promulgated a series of rules to decrease the exposure of coal miners to respirable dust. Starting August 1st 2014, the following rules were effective (Green, 2012):

i. The mine operators are required to carry out sampling for the entire shift. Immediate corrective actions are required should the sampled flow indicate excessive dust-levels;

ii. A ‘normal production shift’ has been defined as a shift when the production level meets or exceeds 80% of the coal-production averaged over the last 30 production shifts;

iii. The number of spots where sampling needs to be carried out was increased. The personnel in-charge of sampling are required to be certified by MSHA;

iv. Increased medical surveillance is required in addition to transfer rights to an area with lower dust concentration, extended to the miners suffering from CWP. An increased sampling of part-90 miners (miners showing signs of CWP) was proposed.

The following provisions were implemented eighteen months after the date of declaration of the rule, beginning February 1st 2016:

i. The continuous personal dust monitor (CPDM) is required to be worn by all part-90 miners and other miners exposed to high respirable dust concentrations;

ii. Sampling frequency was increased, and the miners received resultsfaster.

Since August 1st 2016, the overall permissible concentration limit of dust in mines was reduced from 2.0 to 1.5 mg/m^3 of ventilation air. The standards for miners, including part-90 miners, have been reduced by 50 % from 1.0 to 0.5 mg/m^3 (MSHA, 2014).

2.5 Dust Controls in Underground Coal Mines

Dust can be diluted in different ways, such as control and displacement via ventilation, wetting and capture by using water sprays, and collection and filtration by dust collector. The main goal of these methods is to reduce dust concentration levels for health and safety of workers. Most dust control methods are employed near active workings of a mine since a large amount of dust in an underground mine is generated at the active working face, whether a continuous miner or a longwall shearer (Kissell, 2003). Multiple control techniques need to be applied at the same time because a lower percent of dilutions is achieved by using just one of the techniques, apart from the fact that by removing a miner from the hazardous dusty environment eliminates any threat of exposure (Kissell, 2003).

2.5.1 Dilution via Ventilation

Dilution via ventilation dates back to 1556, when wind-powered fans were used, as shown in Figure 2.5. Numerous upgrades to this ventilation system have been achieved due to research efforts (Reed & Taylor, 2007). This method reduces the concentration of dust by supplying fresh air to all areas where miners are working. Dust can also be moved away from workers by applying displacement to ventilating air, which consists of using the velocity of the ventilated air. This is the most effective dust control technique available, but it tends to be difficult to implement in a mine because the cost of increasing airflow can be substantial, and it is not always fiscally or technically affordable (Kissell, 2003).

Figure 2.5: Ventilation fans, powered by wind (Source: De Re Metallica)

2.5.2 Water-Sprays Application

Today, water sprays are one of the most used dust control methods, and they carry out two important tasks: capturing airborne particles inside water droplets and wetting newly broken material (Kissell, 2003). The sprays create numerous fine water droplets to capture dust once it has become airborne, a practice that generates good results both in theory and in the laboratory. However, there are a few drawbacks in an underground coal mine due to the small amount of airborne particles captured by the water sprays as not all of the airstream passes through the system (Kissell, 2003). Water sprays may also induce airflow that increases a worker's exposure to dust by displacing the dust away from the working face and towards the worker (Kissell, 2003).

According to Kissel, wetting newly broken material has a great impact on dust control, with a large amount of dust remaining on the surface of the material. A well-executed application of this method effectively captures dust and prevents it from becoming airborne. The sprays may be implemented on operative machines themselves, as well on any source that could possibly develop dust, limiting the generated particles from the additional crushing of material (Kissell, 2003).

Selecting operational parameters and the correct nozzle for the application are two key factors in the success of a water-spray system. Investigations at NIOSH recently indicated that full-cone sprays have an average coal dust capture efficiency of about 26.4%. Gravimetric studies, on the other hand, showed a capture efficiency of about 19.6% (Block, 2018).

Shearer clearers, like the one shown in Figure 2.6, tend to have multiple water sprays facing the coal face in order to limit the dust cloud to the face. Spray bars mounted on the main control and drive modules of the shearer also aid in the prevention of dust migrating to other locations. Figure 2.7 shows how sprays are installed on continuous miners to combat generated dust.

Research has substantiated the effectiveness of water sprays. Taylor and Zimmer (2001) showed that there was a high reduction of methane concentration at the face with the use of an exhaust ventilation system in addition to water sprays (Taylor & Zimmer, 2001). It was also proven that water sprays aid on the performance of the flooded-bed dust scrubbers (Goodman, 2000).

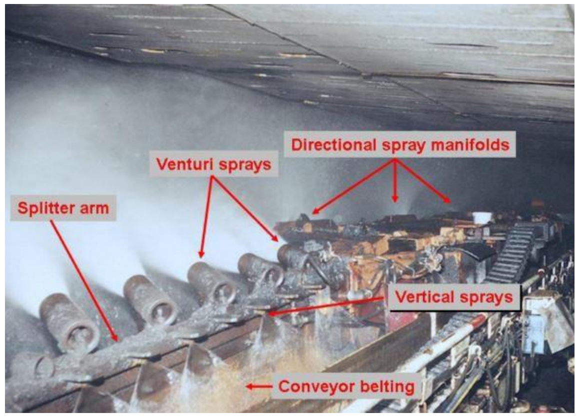

Figure 2.6: Multiple sprays on a longwall shearer (Source: CDC, NIOSH)

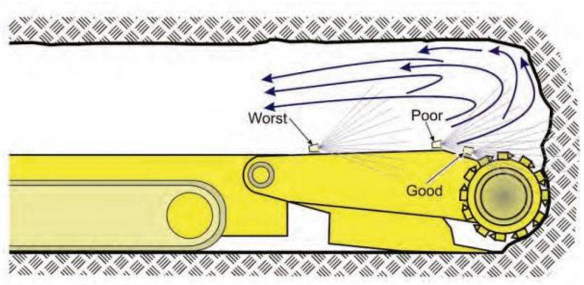

Figure 2.7: Strategically installed location of water sprays on a continuous miner (Colinet., 2010)

Pollock and Organiscak (2007) used different spray nozzles to study their effect on dust capture. Figure 2.8 shows the spray nozzles they used for the tests; these included a hollow cone, a full cone, a flat fan, and an air atomized type.

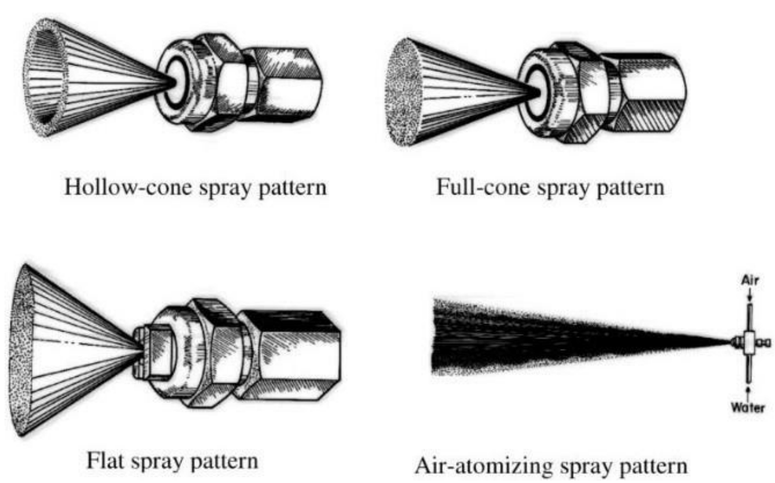

Figure 2.8: Sprays used by Pollock and Organiscak (2007)

The performance and characteristics of the sprays were examined, including the size and the initial velocity of the droplets. The nozzle with a wider spray generated more flow but resulted in lower dust capture. More airborne dust was captured by using nozzles with increased spray pressure (smaller orifices) to generate water droplets of a size akin to that of respirable dust. However, this type of nozzle tends to get clogged more frequently, making it an unsuitable option for underground mining operations (Kissell, 2003). Also, spray nozzles with higher air moving capabilities had less dust cleaning efficiency. The airborne dust capture performance of the four different types of nozzles at different water pressure values is shown in Figure 2.9. An investigation by the US Bureau of Mines has demonstrated how effective water sprays assist in scrubber ventilation (Volkwein & Wellman, 1989).

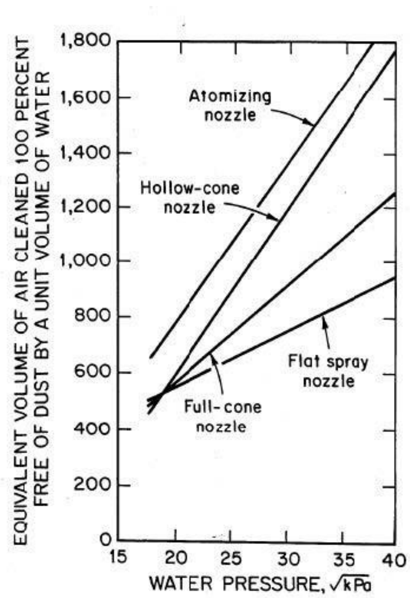

Figure 2.9: Capture performance of nozzles at different pressure (Kissell, 2003)

2.5.3 Dust Collectors

Dust collection systems are more often used in mineral processing plants to reduce dust concentrations (Cecala, et al., 2012). A Hood captures dust and carries it to an air-cleaning device that works along with a fan, as shown in Figure 2.10. Hoods are designed depending on the volumetric airflow rates and the source of dust generation.

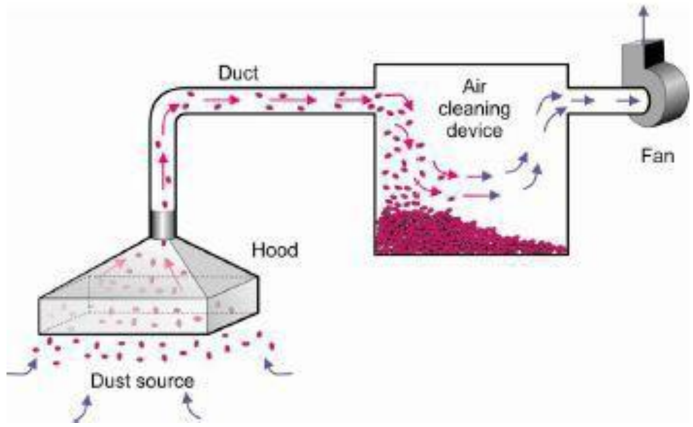

Figure 2.10: Schematic of a simple exhaust system consisting of a hood, duct, air cleaning device and a fan (Cecala, et al., 2012)

A cyclone dust collector, as shown in Figure 2.11, is a low-maintenance dust collector system. It has less efficiency in cleaning smaller dust particles than the previously mentioned system, and it is mainly used as a pre-cleaner system to remove larger dust particles from the air stream. Other dust collection systems are used in mineral processing plants, such as mechanical shakers collectors, baghouse collectors and reverse collectors.

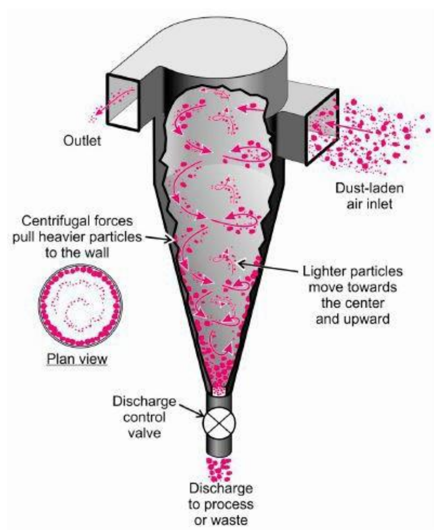

Figure 2.11: Schematic of a cyclone dust collector (Cecala, et al., 2012)

2.5.4 Wet Scrubbers

Wet scrubber dust collectors use water or other liquids to capture dust particles and are mainly used on mining machinery such as continuous miners. Figure 2.12 shows a schematic of a typical wet scrubber dust collector. Certner et al. (1989) studied a wet scrubber with a pneumatic nozzle highlighting the capture efficiency with respect to the mechanisms of inertial impaction, turbulent diffusion and coalescence induced by turbulence. Results of the investigation showed that the inertial impaction was the primary cleaning mechanism. The impaction zone of these scrubbers is composed of the impingement screen and the surface of the vortex chamber, respectively. Examples of wet scrubbing systems are flooded-bed dust scrubbers, used on continuous miners, and Vortecones, used to capture the over-sprayed paint particles on vehicle painting lines. Venturi scrubbers are other wet scrubbing systems that are also widely used (Mayinger & Neumann, 1978).

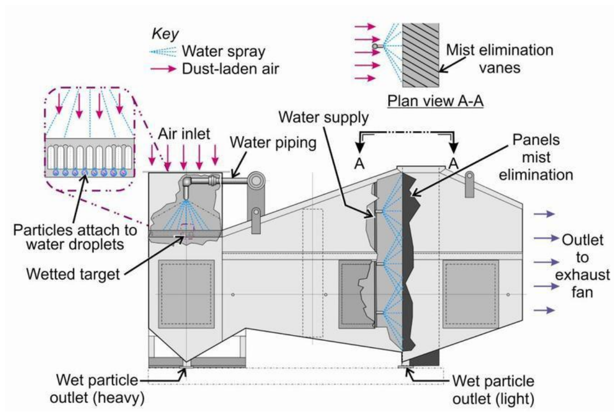

Figure 2.12: Schematic of a wet scrubber dust collector (Organiscak & Page, 2005)

2.5.5 Cutting Head Drum Sprays

Using wet head cutting drums has become a standard practice in the underground mining environment. The main goal of using them is to capture dust at the source of its generation. Sprays are installed on top of the drum vanes, near the cutting vane of the machine. This methodology can be applied to minimize the dust generated at the face on machines like continuous miners, shearers, and road-headers.

This cleaning efficiency practice is also used to lower the ignition potential of coal and to reduce the bit wear (Khair & Achanti, 1998). Figure 2.13 shows A JOY 12CM27 continuous miner with sprays installed on the cutting drum. Drilling machines also use high-pressure water to keep the bits cool and extend the useful life of the equipment

(Tiryaki, 2004). Sprays are also known to be powerful air movers, and they redirect the dust-laden air away from machine operators, the coal face and the rest of the workers.

The Safety in Mines Research Advisory Committee (SIMRAC) stated in one report that wet-head cutting drums on continuous miners, shearers, and road-headers lower dust concentration and help to prevent frictional ignition (Phillips, 1997). Water mounted sprays also douse the "methane puffs" created when a cutting machine works against a solid coal face.

Figure 2.13: Water sprays mounted on JOY 12CM27 cutting drum (Source: Komatsu)

2.6 The Vortecone

The Vortecone is a type of wet scrubber invented at the Institute of Research for Technology Development, at the University of Kentucky. It works as an inertial droplet separator system and was mainly developed to capture over-spray paint particles on an automotive paint line (Salazar, 2012). Figures 2.14 and 2.15 depict the original Vortecone and a schematic of it as depicted in the patent. Geometrical parameters that seem to influence the performance of the Vortecone have been numbered.

The device utilizes the momentum of traveling dust particles to separate them from the moving airstream (Salazar, 2012). It consists of an inlet, a vortex chamber, and an outlet. Water is released close to the inlet as the particle-laden air travels to the vortex chamber. The gradually decreasing cross-section area between the inlet and the chamber forces the fluid to accelerate and then rapidly changes its direction within the vortex chamber. As a result, particles with high inertial energy shift to the outer walls of the Vortecone and get trapped by the water film as the air completes a 360-degree turn. Lastly, the particles that are not captured exit the system through the outlet with the rest of the fluid. (Levy, 2017).

Tianxiang Li, Abraham Salazar, and Kozo Saito (2009) performed a set of practicability tests to evaluate the Vortecone's performance on clearing fly ash from coal-fired power plants. The results of this study showed a cleaning efficiency in removing fly ash of 99.8% with a 30% of energy savings, compared to the cyclone that is normally used. Paint over-spray particles and fly ash both contain particles in the respirable range, making the Vortecone a suitable device to combat dust in the mining sector

Figure 2.14: Vortecone developed at the University of Kentucky (Source: Odyssey, University of Kentucky, 2005)

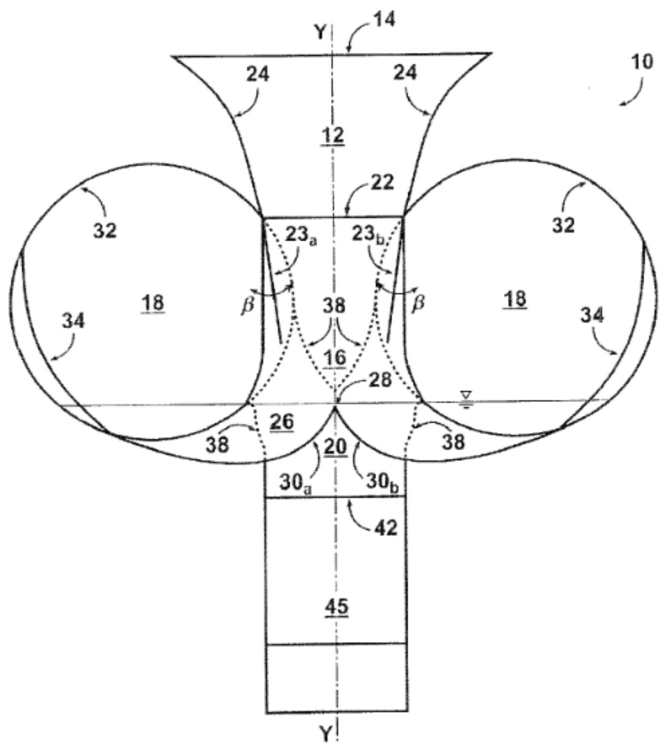

Figure 2.15: Schematic of the original Vortecone Scrubber (USA Patent No. US 8,241,405 B2, 2012)

Chapter 3 Aerosol Particles

Small particles that are suspended in a fluid stream are considered aerosols and could exist either with a wide range of diameters or one discrete diameter. Optical and physical properties of aerosols vary broadly like other characteristics such as shape, size and source of generation. A wide variety of activities in a mine generate dust particles which are suspended in the airflow making them aerosols. These particles in a mining environment could be dust, fume, mist and smoke, all of which can be a threat to the workers' health.

Aerosol particles can be categorized by their sizes and shapes. The most relevant parameters of aerosols for studies on scrubber systems are size, concentration and density. For all the testing in this thesis, coal particles commonly known as keystone mineral black 325 A, was used. This mineral has a bulk density of 1,220 kg/m$^{3.}$

Diameter is the metric unit that is usually used to denote the size of a particle. It represents the length of a perfect sphere from its chord through its center. Nevertheless, aerosol particles tend to have a variety of shapes with most of them being irregular.

The coal dust used for this investigation has diameters between 0.30 – 15.0 µm and are poly-dispersed aerosols because of the wide range of diameters they have. Many practices could be used to describe the distribution of these type of particles. Additionally, particles with less than 100.0 µm diameter are considered to be inhalable; with less than 10.0 µm (also known as PM10)are thoracic, and very dangerous to the lungs. Respirable particles have a diameter less than 4.0 µm and could get deposited in the lungs.

Particle concentration relates to the amount of particle count per unit volume of the fluid and could be measured in terms of a number or mass concentration. The MSHAstandards have been written in terms of gravimetric concentration (mg/m^3) of dust particles underground. A wide variety of sampling equipment also reports the particle concentration in these units. Optical particle counters, as the one discussed later in this investigation, usually classify and report the particle concentration on the basis of diameter.

3.1 Interaction with the Surfaces

There are a variety of ways in which an aerosol particle can interact with solid surfaces. A study conducted by Lifshitz and Kolsky in 1964 showed that for rough and polished surfaces, the coefficient of restitution for collision of particles with the walls varied from 80% to 95% respectively. In 1971, Dahneke studied the collision of perfectly shaped spherical particles with smooth surfaces. He assumed that intermolecular forces and electrical charges on the particles were the dominant factor to attract the particles towards the surface on these studies. Tsai et al simulated the collision and rebound of particles from different types of surfaces.

3.2 Theory of Filters

Filters are instruments used to capture particles from a fluid stream. They can be found in a wide variety of sizes, shapes, and capture mechanisms. In the mining industry, filters are being constantly used in machinery. An example of a filter could be the dust scrubbing systems since they remove particles from the dust laden air. The screen that is incorporated in the flooded-bed dust scrubbers is a fibrous filter. Some of the most important mechanisms of filters are shown in Figure 3.1.

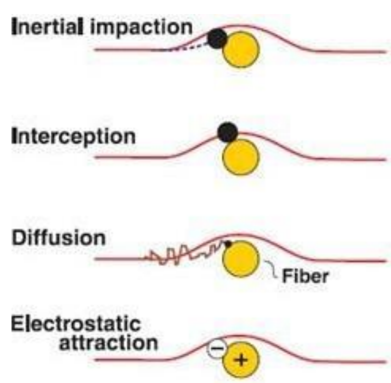

Figure 3.1: Mechanism of particle interception by the filters (Source: CDC, 2013)

The mechanics that take care of the particle capture on filters are the following (Kumar, 2018):

i. Mechanical capture of particles could occur via diffusion, interception, inertial impaction, gravitational sedimentation, dry and wet sieving, and screening.

ii. Electrostatic forces including Coulombic attraction or repulsion, dielectrophoretic force and magnetic separation could lead to an electrical capture of particles.

iii. Diffusion affects particles < 0.1 µm, small particles diffuse away from gas streamlines and have higher chances of striking the filter.

iv. Interception mechanism is most effective for particle size 0.1-1.0 µm; larger particles have higher chances of contacting the filter media.

v. Inertial impaction is effective for particles with diameter exceeding 1.0 µm; these particles have very high momentum compared to smaller ones.

3.3 Theory of Impactors

The impactors are an essential class of systems that are used in aerosol research. Impactors have been improving constantly since Marple initially proposed them in 1976. These mechanisms force the particles to take very quick and sharp turns, as shown in Figure 3.2. Heavier particles tend to hit the impaction surface while the lighter particles follow the stream of the airflow. The impingement screen used for the experiments of this thesis was designed to work as an impactor.

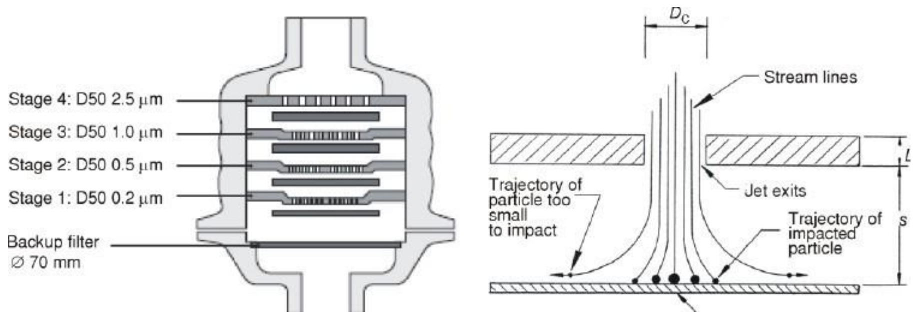

Figure 3.2: Impactor mechanism (Marple & Willeke, 1976)

3.4 Particle Sampling from an Airstream

The airstream is sampled by using the iso-kinetic sampling technique to study the profile of aerosol particles that are flowing in a duct. This technique consists in taking a representative sample from the airstream at an identical velocity as shown in figure 3.3. This must be done to obtain accurate concentration results in the airflow (Wilcox, 1956). Anisokinetic sampling could cause in under or oversampling of particles as shown in Figure 3.4.

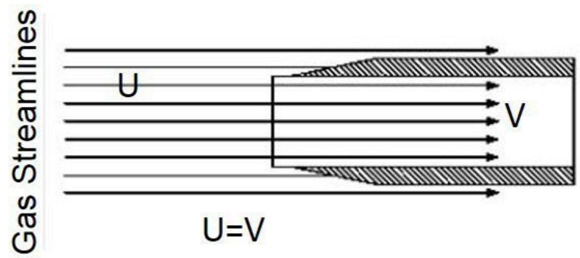

Figure 3.3: A representative set-up of iso-kinetic sampling of the airstream (Source: Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. Hinds)

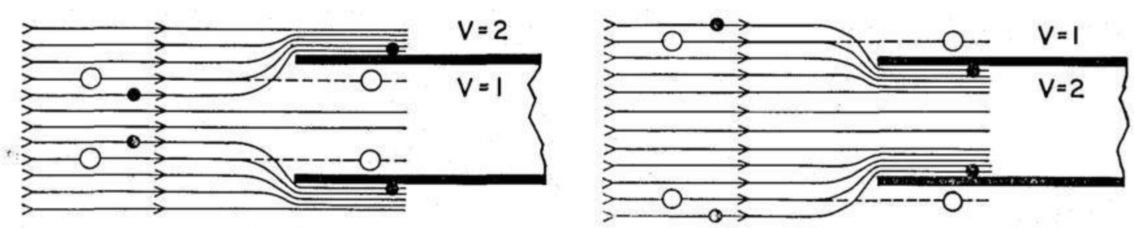

Figure 3.4: The effects of anisokinetic sampling of the airstream (Wilcox, 1956)

The following parameters could also generate particle losses when sampling according to various research:

i. Inertial impaction and turbulent diffusion at the inlet, especially if the system has multiple rapid changes in cross-section area,
ii. Turbulent diffusion at the vertical and horizontal cross sections (Liu, 1974),
iii. Loss at the bends of the duct and circular cross-sections (Pui, 1987) (Mc Farland, 1996),
iv. Gravitational settling in the horizontal sections if the particles are heavy,
v. Inertial impaction at the bends, secondary flows including vortices close to the surfaces,

vi. Image force precipitation due to static electrical charge build-up in the system.

These factors have been considered and applied for all the laboratory procedures described in the following chapter to generate more accurate results when counting particles. Iso kinetic sampling have been used to ensure a representative sample of the three filter systems under study. An auger injection system composed by an Arduino controlled stepper motor has been used to regulate the injection of the coal dust into the system. TSI OPS 3330 has been used to sample the airstream in order to determine the cleaning efficiency of the filters.

Chapter 4 Set-up for the Experiments

4.1 Set-up Overview

For the purpose of this investigation, a laboratory located in the Department of Mining Engineering at the University of Kentucky was used. This lab is entirely dedicated to research related to mining health and safety, specifically in the areas of aerosols and dust-scrubber systems. A wind tunnel set-up was constructed in order to simulate the conditions in a flooded-bed dust scrubber used on continuous miners. Multiple adjustments were made in order to test all the dust-scrubber systems. The screen was fit to the tunnel, minimizing leakage. A reduced scale model of the Vortecone was built for the experiments. The experiments were conducted to establish the influence of airflow and water influx on cleaning efficiency of the filter systems. Figure 4.1 shows the testing set-up used for all the scrubber systems.

Figure 4.1: Scrubber-system testing set-up built for running all experiments

A 25-horsepower (18.64 kW) centrifugal fan, as shown in Figure 4.2, was used to drive the airflow through the ductwork. The fan was controlled by a 60 Hz, 3-phase, 460 V induction motor and has a maximum speed of 3,525 rotations per minute (RPM). An Allen Bradley variable frequency drive (VFD) controlled the rotational speed of the motor in order to achieve the desired flows through the wind tunnel.

The duct was built using aluminum sheets and has inner dimensions of 18” in. by 12”. Each section of the tunnel had identical size of aluminum plate for easier assembly or replacement. The ductwork was constructed in such a way that it allows the use of every scrubber system without making any major changes, which granted minimal efforts when switching from one to another. A Dwyer Instruments STRA Airflow Measurement Station (Dwyer Measurement Station), as shown in Figure 4.3, was installed upstream of the fan;

this station also had a built-in honeycomb structure that worked as a flow straightener, used to maintain good streamlines.

Figure 4.2: Centrifugal fan and variable frequency drive

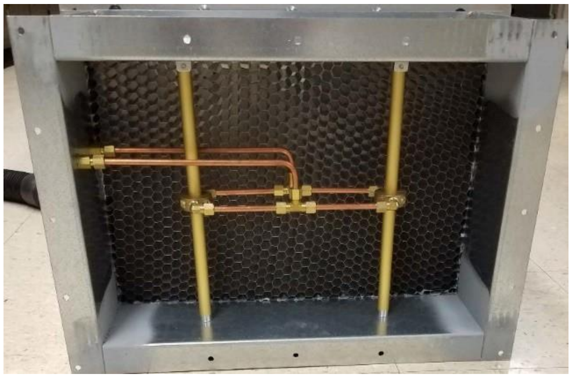

Figure 4.3: Inside of Dwyer STRA Airflow Measurement Station

For the traditional setup of the Vortecone (vertical orientation), two corners wererequired to turn the flow downward into the Vortecone and then horizontal to the outlet. Vane and rails arrangements, as shown in Figure 4.4, were implemented to reduce the amount of shock loss and loss of dust particles due to impaction on bends. For the tests with the Vortecone in vertical orientation, a total of three turns were used in order to fit the entire set-up in the laboratory. For the rest of the filters, including the Vortecone in horizontal orientation, only one turn was required.

Figure 4.4: Vane and Rail arrangement

A fully automated 3D printed auger system, as shown in Figure 4.5, was used to maintain a constant dust injection through the system. An Arduino model Duemilanove was programmed to control the rotations of the auger by sending a code to the stepper motor attached to it. The code included parameters, such as idle time between steps, angular velocity and the angle per step, which were tested until reaching the desired feed rate.

The goal was to inject 5.0 gm of coal dust over 8.0 minutes; the coal mass was carefully measured by using a digital scale. This ensured that the ratio of particle count over the sampled volume did not exceed the recommended operational range of 3,000 particles/cm3. The dust went through a conveying eductor, which vacuumed and aerosolized the particles while conveying it into the ductwork. A compressed air line created the suction in the conveying eductor inlet and made possible the acceleration of air through the discharge of the device into the pressurized wind tunnel. Figure 4.6 depicts a general cross-section of an eductor.

Figure 4.5: Auger-feeder system for a controlled injection of dust-particles

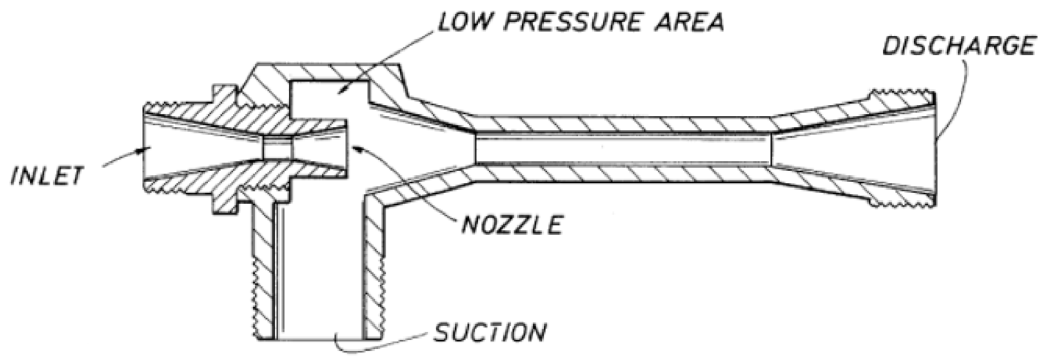

Figure 4.6: General cross-section of a Conveying Eductor (Crabtree, 1999)

4.2 Sampling and Instrumentation

A total of two TSI OPS 3330s, as shown in Figure 4.7, were used to count and size the dust particles for this research. One of them was installed upstream of the dust-scrubbing system in order to analyze the feed sample. The OPS installed downstream was used to analyze the remaining air. This optical particle counter has a measurement range of particles from 0.3 to 10.0 µm, and most of the important parameters are shown in Table 3.1.

Figure 4.7: TSI optical particle counter 3330 (Source: TSI)

Table 4.1: TSI OPS 3330 most important parameters (Source: TSI)

Parameters	Values
Sampling Time	≥ 1 s, user adjustable
Particle sizing range	0.3-10 µm over 16 channels
Sample flow rate	1.0 L/min
Sheath flow rate	1.0 L/min
Operating conditions	0 – 45° C 0 – 96% RH
Aerosol medium	Air only
Data storage	5 MB on-board memory (30,000 samples)
Interfaces	USB, Ethernet or USM flash drive
Display	Digital, 5.7 in. color touchscreen
Gravimetric sampling	37 mm filter, removable 37 mm cartridge
Vacuum source	Internal pump
Light source	Laser diode

Figure 4.8 depicts the mechanical mechanism of the OPS, showing the aerosol inlet, laser measurement and photodetection, and other operational parameters.

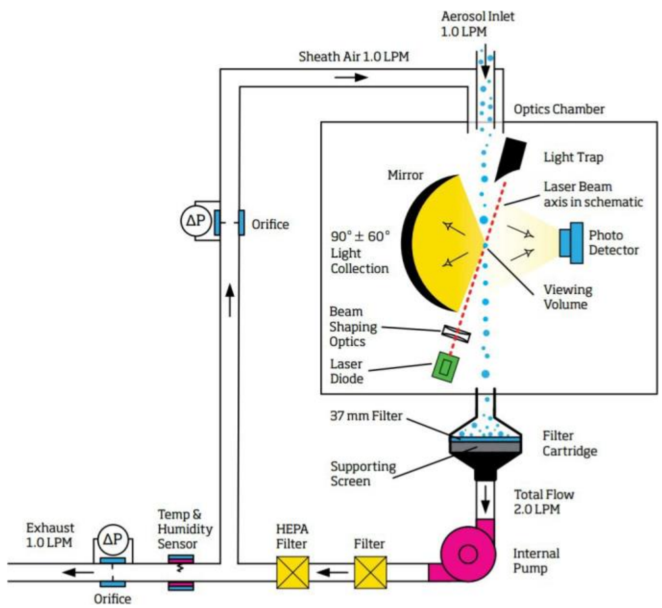

Figure 4.8: TSI OPS 3330 Internal Operation (Source: TSI)

A high-pressure differential between the sampling probe and the discharge of the OPS was avoided to prevent malfunctions in the instrument. Due to this, the manufacturer (TSI) recommends a maximum pressure difference of 750 Pa (3.0 in. wg.) between both the inlet and the outlet ports of the optical particle sizer. To keep the pressure difference at minimum levels, the sampled airflow was circulated back into the ductwork, upstream of the filter system but downstream of the sampling station. The OPS located downstream was used to sample the depleted air, which was passed through a desiccant dryer, as shown in Figure 4.9, in order to remove all the moisture before the analysis run by the OPS.

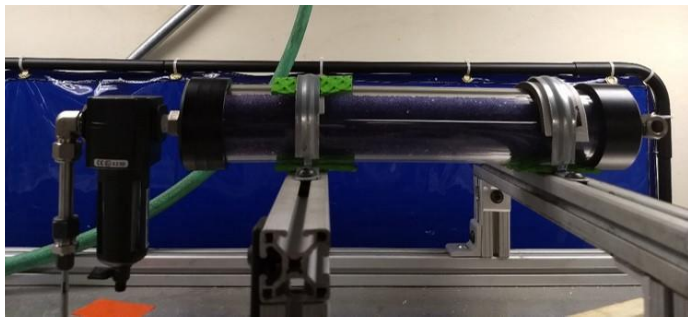

Figure 4.9: Desiccant dryer to absorb moisture from the sampled airflow

Using suitable nozzles, as shown in Figure 4.10, was crucial to sample the air iso-kinetically while not impacting the flow near the sampling tip. These nozzles were designed to ensure that the airstream was sampled isokinetically; these were 3D printed and placed on the sampling tube. These nozzles were designed with specific diameters to ensure the amount of flow through the sampling tube be 1.0 lit/min. The nozzles had tobe placed at specific locations in the duct in order to achieve this flow rate.

Figure 4.10: 3D printed sampling nozzles

To introduce the desired amount of water into the system, a single solid wide-angle cone-shaped water spray model 1/2 HH-40 WSQ was used. To monitor and control the flow of water, a flow control valve with a digital flow meter was attached in series with the water-supply hose. Figure 4.11 shows the spray cone used for these tasks.

Figure 4.11: Full cone shaped water spray 1/2 HH-40 WSQ

Chapter 5 Design of experiments and results

This thesis presents the results from a total of 18 tests, run to determine the relation between the amount of water flow injected into the system and the cleaning efficiency on each one of the filter systems. Tests were done in a random fashion; all experiments were repeated three times in order to minimize any systematic errors in the procedures. Water flows were set at 2.0 gpm (7.57 lit/min), 4.0 gpm (15.12 lit/min) and 6.0 gpm (22.72 lit/min). Additionally, tests were also run in a dry condition (no water flowing through the system), so that the difference between the curves with and without water flow could be compared. Airflows were set at 600 cfm and 800 cfm (0.28 m^3/s and 0.38 m^3/s respectively). JMP statistical software was used to generate the sequence in which the tests wereconducted.

5.1 Vortecone: Vertical Orientation

For this set of experiments, the Vortecone was installed in such a way that the inlet was oriented in vertical orientation, facing upwards, as shown in Figure 5.1. As mentioned in Section 4.1, vane ad rail arrangements were implemented into the ductwork to reduce the amount of shock loss and loss of dust particles due to impaction on bends, creating a smooth flow of air at the corners.

Figure 5.1: Set-up of the Vortecone on vertical orientation

As previously mentioned, the tests had four water flow rates (including the dry condition) and two different airflows. The coal-dust particles were injected using the auger-feeder system, shown in Figure 4.5, along with compressed air. Particles were counted and sampled both upstream and downstream of the Vortecone. The difference between particle mass concentration, reported by both OPSs (upstream and downstream), was the cleaning efficiency. The water injection system was aligned with gravity, facing the airflow. Figures **5.1** and 5.3 show the curves corresponding to cleaning efficiency of the Vortecone in vertical position for different airflows, water flows, and the condition in which there was no water flowing through the system. Tables 5.1 and 5.2 show the statistical analysis of the curve fit to the form of maximum exponential growth. These curve fits were generated using SigmaPlot software.

The cleaning efficiency, η of curves are expressed by equation 5.1 as,

$$\eta = a(1 - e - bd) \qquad (5.1)$$

where, a is a multiplication factor. The factor, b is strongly related to the mechanism of the scrubbing system and the flow through it. A higher value of b makes the cleaning system more efficient at the given flow.

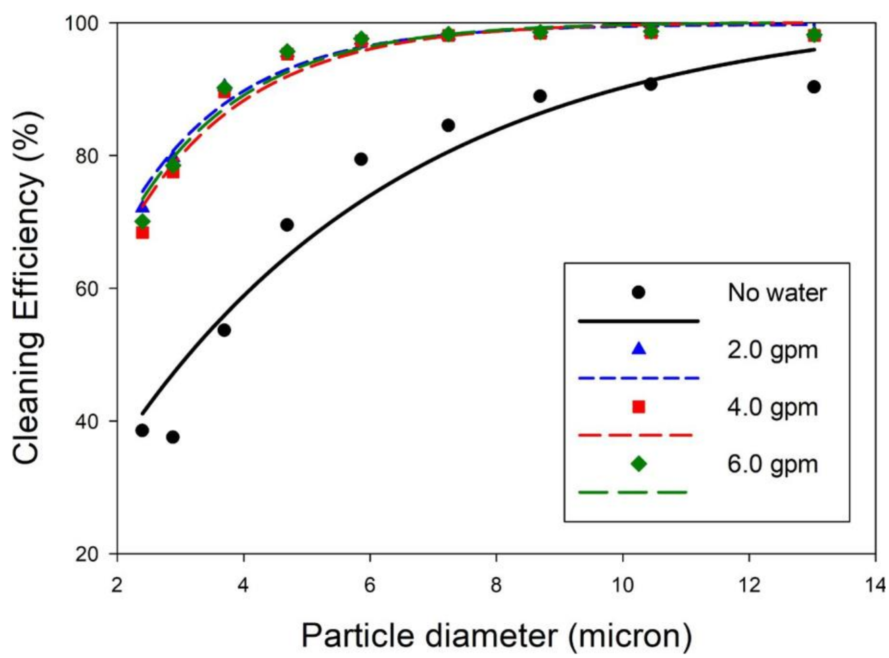

Figure 5.2: Impact of water inflow on the cleaning efficiency by mass of the Vortecone on vertical orientation for an airflow of 600 cfm (0.28 m^3/s)

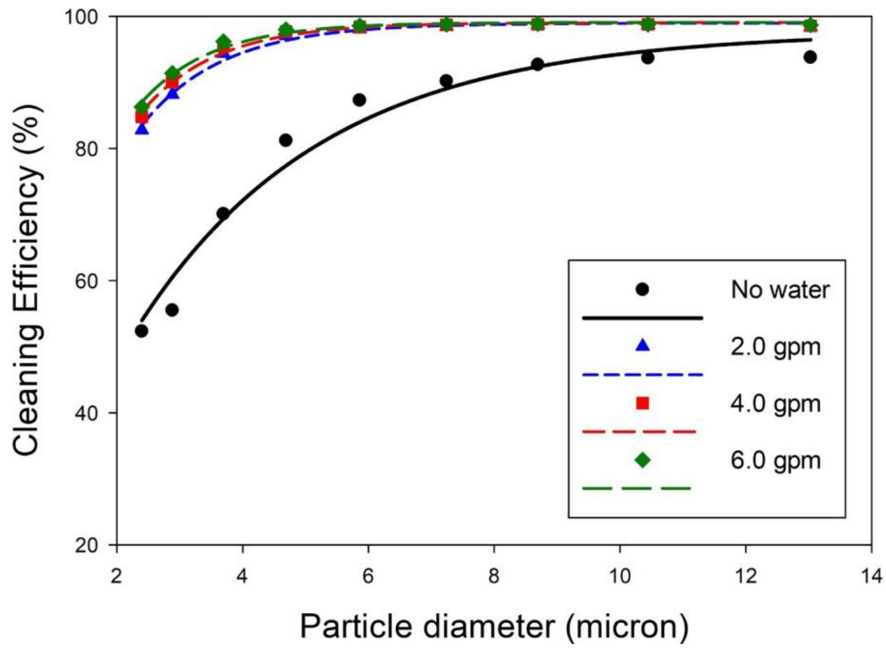

Figure 5.3: Impact of water inflow on the cleaning efficiency by mass of the Vortecone on vertical orientation for an airflow of 800 cfm (0.38 m^3/s)

Table 5.1: Statistical analysis of the Vortecone on vertical orientation for a flow of 600 cfm (0.28 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.93	0.96	0.99	0.95
a	102.19	99.77	99.076	100.11
b	0.22	0.57	0.83	0.55
Standard Error (a)	6.53	0.94	0.26	1.22
Standard Error (b)	0.032	0.026	0.016	0.031

Table 5.2: Statistical analysis of the Vortecone on vertical orientation for a flow of 800 cfm (0.38 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.97	0.99	0.99	0.99
a	97.701	98.99	99.076	99.11
b	0.34	0.77	0.83	0.88
Standard Error (a)	2.16	0.28	0.26	0.24
Standard Error (b)	0.023	0.015	0.016	0.017

5.2 Vortecone: Horizontal Orientation

The previous test set-up was changed slightly, placing the Vortecone with its primary axis perpendicular to gravity, as shown in Figure 5.4. Due to lack of space in the laboratory, the use of vane and rails to accommodate the ductwork were obligatory in this case, so only one turn was necessary to make it work. Note that there was a total of three turns on the Vortecone vertical orientation tests. The horizontal orientation is the most likely to be used on continuous miners, shearers, and at other locations in a mine, if implemented.

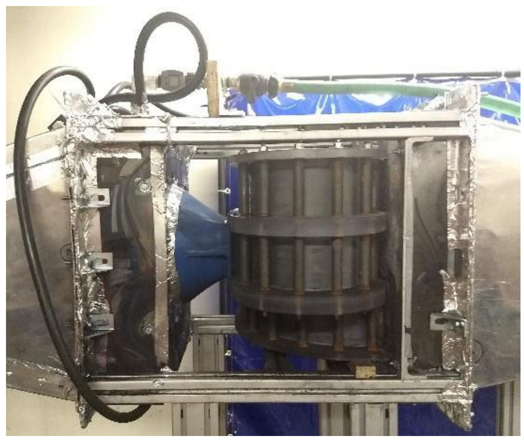

Figure 5.4: Set-up of the Vortecone on horizontal orientation

The same test parameters used on the vertical orientation were used for the experiments in horizontal orientation. Laboratory experiments were carried out to determine the impact of water influx on the cleaning efficiency with airflows set at 0.28 m^3/s (600 cfm) and 0.38 m^3/s (800cfm). Water flows were injected at a rate of 7.57 lit/min (2.0 gpm), 15.12 lit/min (4.0 gpm), and 22.72 (6.0 gpm), with an additional state in which there was no water flowing through the system (dry condition). Five grams of Keystone mineral black 325 A were weighed and fed into the duct over 8.0 minutes using the controlled auger feeder. To prevent malfunctions, a controlled injection of coal-dust ensured that the overwhelming limits of both OPSs were not reached.

The difference between the reading of both OPSs was then compared to determine the cleaning efficiency by downloading the data from the equipment and using the TSI Aerosol Instrument Manager software to convert the particle number to mass concentration. This data was then used to plot the cleaning efficiency curves and determine the contribution of water influx. Figures 5.5 and 5.6 show the plots of cleaning efficiency, and Tables 4.3 and 4.4 show the statistical analyses of these plots.

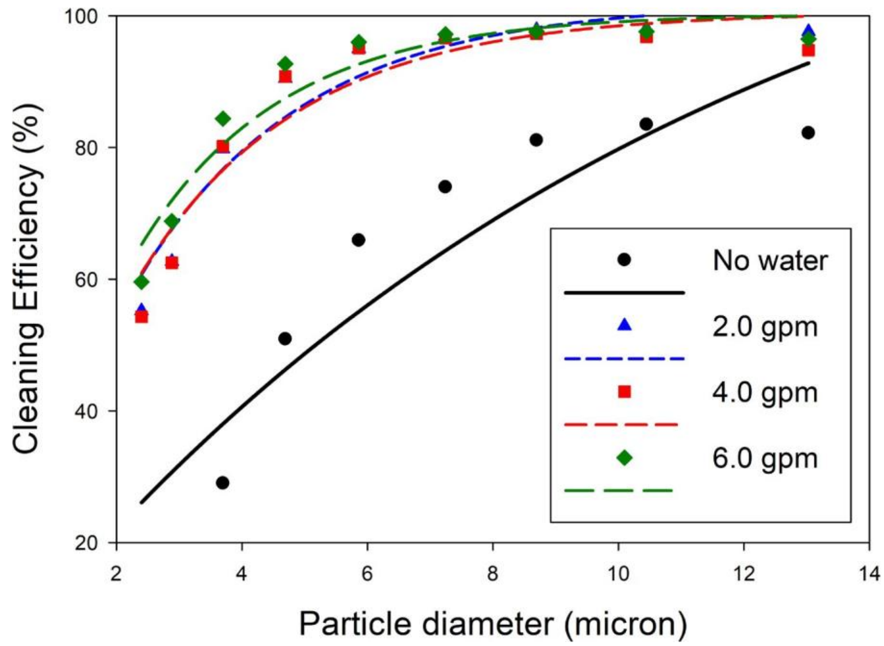

Figure 5.5: Impact of water inflow on the cleaning efficiency by mass of the Vortecone on horizontal orientation for an airflow of 600 cfm (0.28 m^3/s)

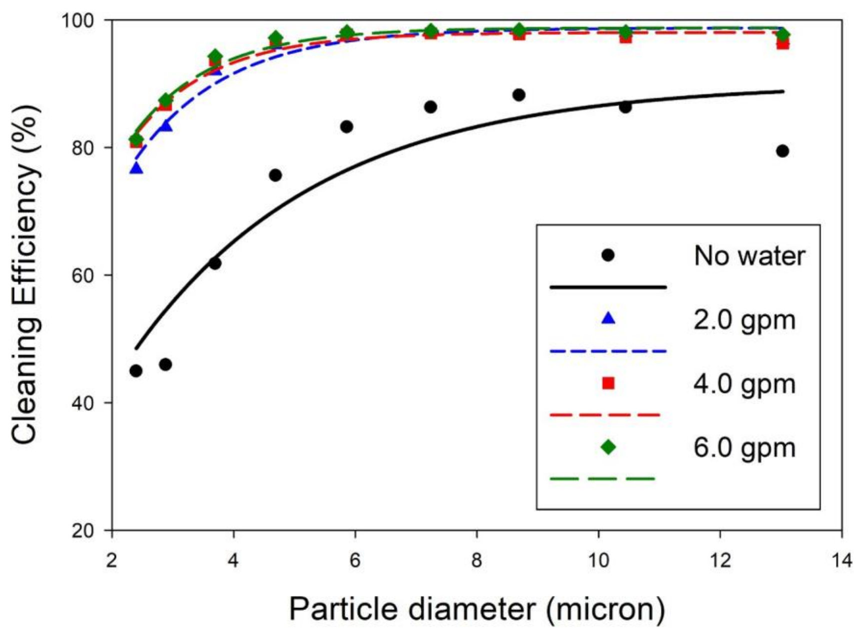

Figure 5.6: Impact of water inflow on the cleaning efficiency by mass of the Vortecone on horizontal orientation for an airflow of 800 cfm (0.38 m^3/s)

Table 5.3: Statistical analysis of the Vortecone on horizontal orientation for a flow of 600 cfm (0.28 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.84	0.93	0.901	0.92
a	134.68	102.026	100.58	100.36
b	0.089	0.38	0.39	0.44
Standard Error (a)	53.13	2.87	3.28	2.35
Standard Error (b)	0.053	0.035	0.043	0.039

Table 5.4: Statistical analysis of the Vortecone on horizontal orientation for a flow of 800 cfm (0.38 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.86	0.96	0.96	0.97
a	90.13	98.76	98.046	98.78
b	0.32	0.66	0.76	0.75
Standard Error (a)	4.77	0.72	0.56	0.48
Standard Error (b)	0.051	0.027	0.029	0.024

5.3 Conventional Screen

Today, continuous miners use a fibrous-type conventional screen with 10-30 layers of finely woven metal threads in their flooded-bed dust scrubbers. These are constantly covered by a membrane of water produced by a full-cone spray, which helps with both capture of the dust-particles and the cleaning of the screen to prevent an accumulation of dust. One of these screens with 20 layers was obtained from a manufacturer to analyze the impact of water flow on cleaning efficiency.

The screen was installed at 45° in the direction of the flow to mimic a real case scenario in a continuous miner flooded-bed dust scrubber. Figure 5.7 shows the conventional screen installed in the duct-work, and Figure 5.8 shows the operating cone-shaped spray at maximum capacity.

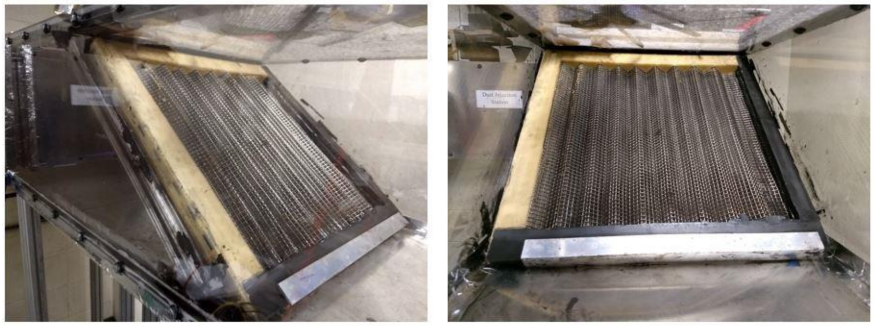

Figure 5.7: Conventional screen inside the ductwork

Figure 5.8: Cone-shaped spray covering conventional screen with a film of water

A pressure-flow curve for the screen was generated. To do so, average airstream velocity and total pressure were measured by changing the frequencies set on the VFD at the pressure measurement station. The resulting magnitude of velocity was converted to appropriate volumetric flow rates through the system. Figure 5.9 shows the curve plotted with the obtained values.

An iso-kinetic sampling technique was used at known airflows to determine the impact of water flow on the cleaning efficiency. The system curve was then used to locate the corresponding frequency to the desired flows of 0.28 m^3/s (600 cfm) and 0.38 m^3/s (800 cfm). The points of the average velocities corresponding to the flows were located. The iso-kinetic sampling probes were installed and changed according on the airflow in each test. There were sampling tubes connecting the probes to the sampling port of the TSI OPS 3330 on each side of the filter screen, upstream and downstream.

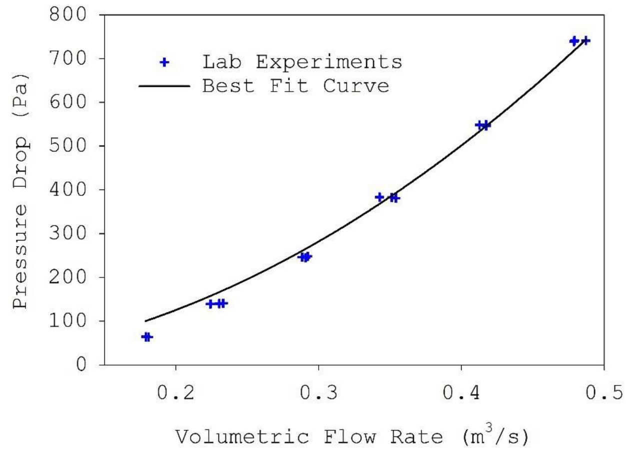

Figure 5.9: Conventional screen pressure drop curve

The same randomly designed and balanced experiments used on both previous tests were employed for the conventional screen tests. The goal was to feed 5.0 grams of mineral black 325 A coal dust into the system in a time frame of 5.0 minutes. The difference in particle-mass concentration recorded by the OPSs, upstream and downstream, yielded the cleaning efficiency, which was then used to analyze the impact of water in this type of filter system. Figures 5.10 and 5.11 show the plots for the cleaning efficiency, including the dry condition (no water through the screen). Tables 5.5 and 5.6 show the corresponding analyses for both plots.

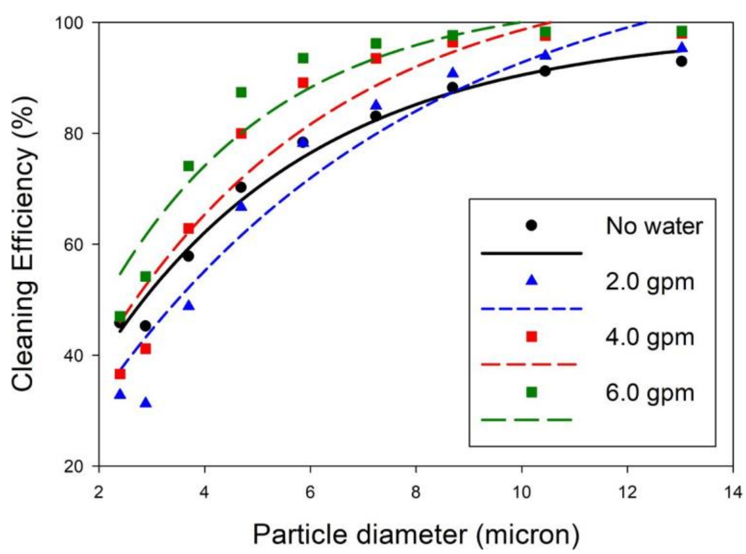

Figure 5.10: Impact of water inflow on the cleaning efficiency by mass of the Conventional screen for an airflow of 600 cfm (0.28 m^3/s)

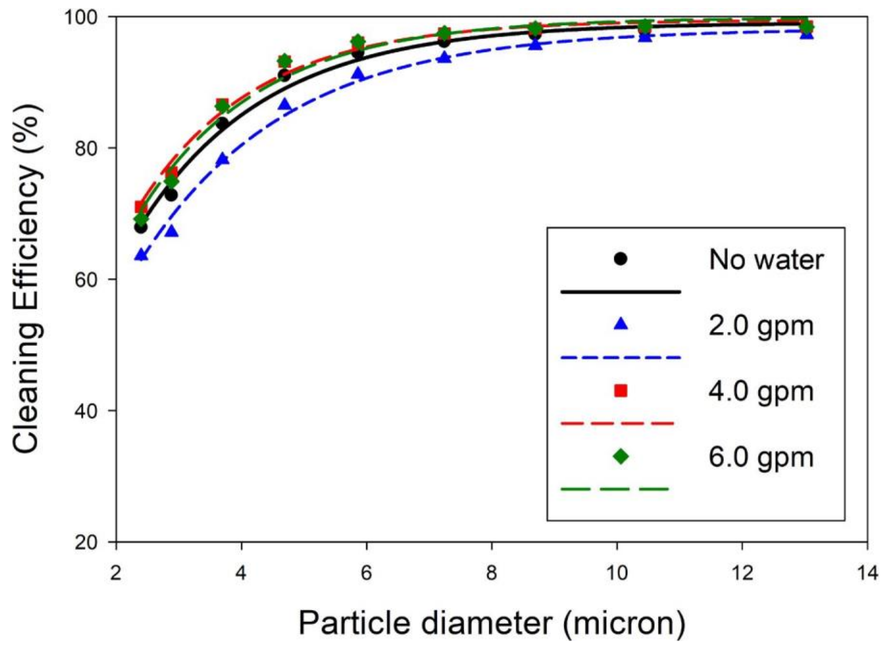

Figure 5.11:Impact of water inflow on the cleaning efficiency by mass of the Conventional screen for an airflow of 800 cfm (0.38 m^3/s)

Table 5.5: Statistical analysis of the conventional screen for a flow of 600 cfm (0.28 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.99	0.99	0.99	0.98
a	99.078	98.19	99.51	99.83
b	0.49	0.43	0.53	0.51
Standard Error (a)	0.70	0.71	0.64	0.89
Standard Error (b)	0.014	0.011	0.015	0.019

Table 5.6: Statistical analysis of the conventional screen for a flow of 800 cfm (0.38 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.98	0.93	0.90	0.91
a	98.81	115.58	110.38	104.94
b	0.25	0.16	0.22	0.31
Standard Error (a)	2.59	11.77	8.61	4.63
Standard Error (b)	0.016	0.032	0.041	0.039

5.4 Impingement Screen

The impingement screen operates like an inertial impactor. The system was made of three individual screens with long parallel slits measuring 6 mm in width, as shown in Figure 5.12. The first and the third screens were identical to each other. The second screen had its slits displaced by 6.0 mm in the plane of the screen itself. Therefore, the screen system was blind to straight flows. The dust-laden air was forced to make sharp turns at all the screens. This ensured that there was a near-perfect split of airflows at thescreens.

The design was conceptualized after an iterative procedure where the screens were first separated by 6.0 mm. The separation was reduced in steps of 1.0 mm. The three screens were spaced by distances of 3.0 mm and 2.0 mm, respectively, following the airflow direction in the final design. This was chosen because the pressure drops began to rise for the same airflow at this separation, which in turn indicated acceleration of airflows.

The lighter air could negotiate these turns easily; however, the heavier dust particles could not follow the streamlines of air due to their mass. Unlike the flow through an impingement screen of a conventional flooded-bed scrubber system, which acts as a porous medium, the trajectory of particles could be described with utmost certainty. Particles hit the solid surfaces of the screen system, which were kept wet by a water spray installed upstream of the screen system. The film of water, together with the screen, served as the filter that trapped the dust particles, thereby cleansing the dirty air. The spent water could now be recycled back into the system, making this set-up a self-sufficient, zero-dischargesystem.

Figure 5.12: The designed impingement screen

Figure 5.13 shows the installation of the impingement screen segment prior to its inclusion to the ductwork set-up.

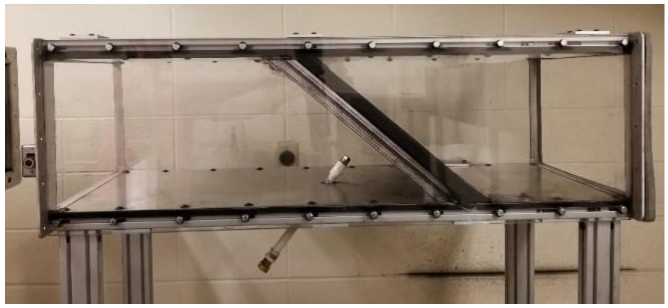

Figure 5.13: Segment were the impingement screen was installed

Due to limitations in detection of the optical-particle sizer, and to avoid any type of error in the particle reading due to the set-up of the experiments, only the results for particles with physical diameters exceeding 2.0 microns were considered. Figure 5.14 and Figure 5.15 show that the cleaning efficacy is enhanced slightly at some point with an increased flow of water. Curves of best fit for maximum exponential growth are also shown. Tables 5.7 and 5.8 show the statistical analyses for their corresponding plots.

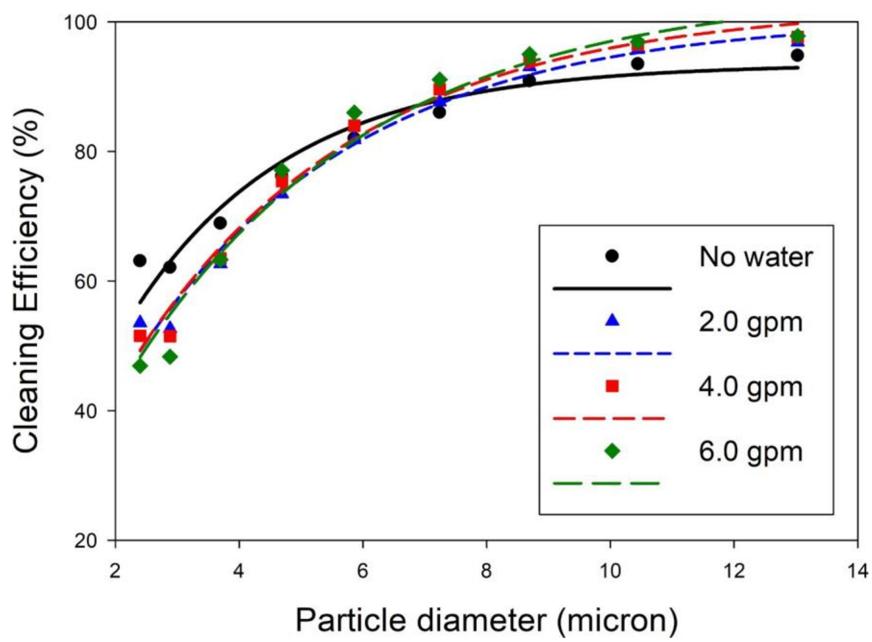

Figure 5.14: Impact of water inflow on the cleaning efficiency by mass of the impingement screen for an airflow of 600 cfm (0.28 m^3/s)

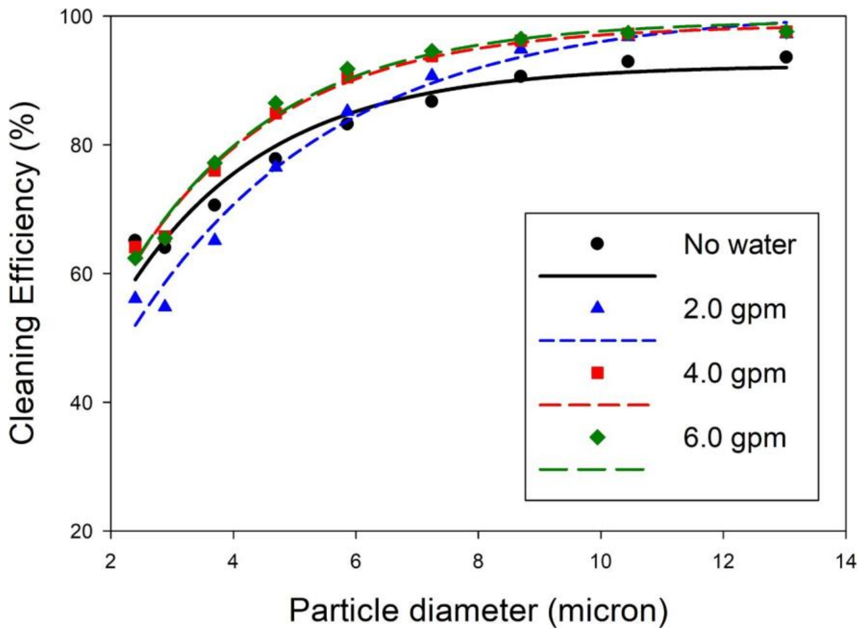

Figure 5.15: Impact of water inflow on the cleaning efficiency by mass of the impingement screen for an airflow of 800 cfm (0.38 m^3/s)

Table 5.7: Statistical analysis of the impingement screen for a flow of 600 cfm (0.28 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.94	0.98	0.98	0.97
a	93.52	100.67	102.66	105.103
b	0.39	0.28	0.27	0.26
Standard Error (a)	1.96	1.96	2.12	3.53
Standard Error (b)	0.028	0.015	0.016	0.022

Table 5.8: Statistical analysis of the impingement screen for a flow of 800 cfm (0.38 m^3/s)

Parameters	No water	2.0 gpm (7.57 lit/min)	4.0 gpm (15.14 lit/min)	6.0 gpm (22.71 lit/min)
Adj. R^2	0.94	0.98	0.99	0.99
a	92.38	101.022	98.69	99.37
b	0.46	0.301	0.41	0.41
Standard Error (a)	1.73	2.056	0.89	0.99
Standard Error (b)	0.029	0.017	0.013	0.014

For the tests with the Vortecone in vertical orientation, the cleaning efficiency significantly improved with the airflow through the system. There was no improvement in the particle capture when the water flow rate was increased. Water film covers the Vortecone walls, making it a highly efficient non-clogging scrubbing system that requires a small amount of water to achieve high cleaning efficiency, as shown in Figures 5.2 and 5.3.

Similar results were obtained when the Vortecone was in the horizontal orientation. However, by increasing both air and water flows, we found a slight increase in cleaning efficiency. Figures 4.5 and 4.6 show cleaning efficiency curves for tests with the Vortecone in the horizontal orientation. The influence of water flow rate was more pronounced here because the motion of water film was strongly influenced by gravity. The top surface of the Vortecone might not have been utilized properly for film formation.

Water flow was found to have a significant influence on the cleaning efficiency of the conventional screen. An increased water flow rate resulted in higher particle captures. This could be due to the conventional screen needing constant cover by a film of water in order to capture more dust particles. Figures 4.10 and 4.11 show the cleaning efficiency curve of the conventional screen when the water flow was 2.0 gpm, where particles of 4.0 microns' diameter were captured, was about 55%.

We can also see, in Figures 4.10 and 4.11, that as water flow rate increased up to 6.0 gpm, the particles with the same diameter were captured with a cleaning efficiency of about 65%. By increasing the airflow to 800 cfm (0.38 m^3/s), there was similar improvement when the water flow rate was greater. The difference between 2.0 gpm and 6.0 gpm was not as notable as the results obtained from the 600 cfm (0.28 m^3/s) tests. This could be because higher airflows saturated the screen with water even at low water inflow rates.

The cleaning efficiency on the impingement screen was not considerably affected by the incoming water flow as with the conventional screen. This could be attributed to its solid, impermeable structure. Figure 4.14 shows the 600 cfm (0.28 m^3/s) airflow tests, indicating cleaning efficiency was only slightly affected by particle sizes upwards of approximately 7.00 microns. The difference of capture efficiency, with respect to the water rates from this point on, was not noticeably different, while in the tests with 800 cfm (0.38 m^3/s), there was an improvement in cleaning when 4.0 and 6.0 gpm were applied to the system. In the

600 cfm (0.28 m^3/s) tests, the difference was not noticeable. Figure 4.115 shows the cleaning efficiency curves for an airflow of 800 cfm (0.38 m^3/s).

Chapter 6 Conclusions and Future Work

6.1 Conclusion

This thesis presented the impact of injected water flow rate for a dust scrubbing system to aid particle removal from a dust laden air. A conventional screen such as the one found in a flooded-bed dust scrubber system of a continuous miner, the Vortecone and a newly designed impingement screen were tested and compared to achieve this goal. This research also helped to determine which of the filters is more convenient for industrial use, depending on the application needs.

Flooded-bed dust scrubbers nowadays require the practice of certain maintenance procedures such as the replacement of the demister, a change of filter screen, and full traverse air reading to determine scrubber efficiency. Some of these practices are performed on every shift and others are mandatory on a weekly or monthly basis. These types of procedures consume time, which could be translated into production cost losses for the mining site.

The developed scrubbing filters require minimum to no maintenance being non-clogging systems, which make them an optimal filter device if they were to be used in flooded-bed dust scrubbers. The impingement screen was design to be an immediate substitute of the conventional fibrous screens, and the results showed that isperfectly capable to replace it. There are still more improvements that can be done to improve even more its capture efficiency rate. These modifications are recommended in section 6.1. The Vortecone also proved its capabilities to capture dust particles from an airstream. It showed to be the most efficient scrubber system out of the three and could possibly work as not only a scrubber system but a particle cleaner in general. This cleaning filter has proven to work with overspray paint particles and coal dust obtaining amazing results. Taylor (2019) performed a set of laboratory tests with silica dust on her redesigned version of the Vortecone, getting positive results from the cleaning efficiency curves.

Testing showed that both the Vortecone and impingement screen have great cleaning efficiency overall compared to the results obtained for the conventional screen. The only filter that was found to be water-flow rate dependent was the conventional screen. The system that requires the lowest amount of water to achieve the best dust capturing rate was the Vortecone. The cleaning efficiency capabilities and self-maintenance qualities of this device show that is a perfect candidate to replace the flooded-bed dust scrubber conventional screen. The Vortecone must still be tested in extreme real life conditions, with advancements made on this device, those tests can be done in the near future.

6.2 Future work and recommendations

Following are suggestions for further work expanding on what is presented in this thesis.

The impingement screen design could be modified to achieve better cleaning efficiency. Changes could include spacing of the screen layers and the size and shape of the slits to force the aerosol particles to take even tighter turns making them more prone to separating solids from fluids. Water recycling should be considered throughout the testing phase. In practice, recycling the water will add efficiencies to the whole filter system and remove dependency on an outside water source. Experiments could also be run using surfactants to replace water as the cleaning fluid.

For the Vortecone, a horizontal design with improvements to make it more suitable for a continuous miner should be considered. The model used for this investigation had two outlets and most of the particles were forced by gravity to travel through the bottom outlet. Taylor (2019) redesigned it with just one outlet and to be able to operate at higher airflows as would be present in a mine environment such as 8,000 cfm and 10,000 cfm. Unfortunately, those airflows were impossible to achieve with the laboratory equipment used. Computational Fluid Dynamics models showed that the cleaning efficiency on the redesigned Vortecone increased as airflow increased (Taylor, 2019). This new version of the Vortecone was built to generate low pressure drops across the system. The results were really encouraging showing that the pressure drop was much lower than both the original Vortecone and the conventional screen. This redesigned Vortecone should betested under high airflows in a manner consistent and comparable to the results presented in this thesis.

Power consumption should be considered while selecting one of the systems under study. Kumar (2018) calculated the power consumption on the Vortecone in his dissertation.

Calculating the power requirement for the impingement screen and the conventional fibrous screen could determine which of the filter is the best feasible system in terms of cost/cleaning efficiency.

There will always be room for imagination to make changes on the design of the Vortecone and the impingement screen as well as finding suitable applications for them. That is why the author of this thesis encourages the reader to investigate more about the improvement of the presented systems.

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Appendix

Arduino code for stepper motor

```
#include <Wire.h>
#include <Adafruit_ADS1015.h>

Adafruit_ADS1115 ads(0x48);
float Voltage = 0.0;

void setup(void)
{
  Serial.begin(9600);
  ads.begin();
}

void loop(void)
{
  int16_t adc0; // we read from the ADC, we have a sixteen bit integer as a result

  adc0 = ads.readADC_SingleEnded(0);
  Voltage = (adc0 * 0.1875)/1000;

  Serial.print("AIN0: ");
  Serial.print(adc0);
  Serial.print("\tVoltage: ");
  Serial.println(Voltage, 7);
  Serial.println();

  delay(1000);
}
```

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Intellectual Property

- Filter assembly and scrubber section for a continuous miner [patent application with the United States Patent and Trademark Office]

Peer Reviewed Journal Manuscripts (Submitted)

1. Kumar, A.R., Schafrik, S., & **Velasquez, O.** (2019). Designing, CFD Modeling, and Laboratory Testing of a Non-Clogging, Self-Cleaning Impingement Type Dust Filter. Mining, Metallurgy & Exploration.

Conference Proceedings Reviewed by Abstract

1. **Velasquez, O.**, Kumar, A.R., Schafrik, S., & Wedding, W.C. (2018). Computational fluid dynamics modeling of dust capture by a non-clogging screen system for a flooded-bed dust scrubber. SME Annual Conference and Expo. [Preprint 18-077, 4p]. Minneapolis, MN.

2. Kumar, A.R., **Velasquez, O.**, Schafrik, S., & Wedding, W.C. (2018). Computational fluid dynamics modeling of an appropriately sized Vortecone scrubber for installation on continuous miners. SME Annual Conference and Expo. [Preprint- 18-102, 5p]. Minneapolis, MN.

Professional Presentations

1. Kumar, A.R., Velasquez, O., & Schafrik, S. (2018). Laboratory experiments to promulgate a Vortecone scrubber as an efficient dust cleaning System. SME Annual Conference and Expo. Minneapolis, MN. [Graduate student poster]

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